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Ceramic Materials for Rolling Element Bearing Applications

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Ceramic Materials for Rolling Element Bearing Applications

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ABSTRACT

Advanced ceramics, silicon nitride ceramics in particular, offer the potential for significant performance increases in rolling element bearings. This chapter reviews the properties of candidate ceramic materials relevant to rolling element bearing performance. The behavior of fully dense silicon nitride for a variety of bearing performance factors including rolling contact fatigue, lubrication behavior, and failure mode is reviewed. Processing advances are briefly described, and experience in actual applications is discussed.

I. INTRODUCTION

Rolling element bearings for use at very high speeds or in extreme environments are performance limited by the density, strength, corrosion resistance, wear resistance, and other constraints of traditional bearing materials. Modern high performance ceramics can provide the combination of material properties required to overcome these limitations. The present line of development of ceramic rolling element bearings was initiated in the late 1960s, when the availability of fully dense hot-pressed silicon nitride coincided with a growing awareness that new materials would be required to meet the evermore stringent demands imposed on aircraft gas turbine bearings [1]. Accordingly, in the 1970–1980 time period a variety of feasibility demonstrations and basic studies established that silicon

nitride rolling elements could significantly increase bearing performance. However, the collective results of these efforts also pointed out that the best fully dense silicon nitride available at that time had insufficient reliability and reproducibility to meet high performance bearing requirements. Thus, during the 1980–1985 time period, efforts at various laboratories around the world focused on process modifications and controls to increase the reliability of silicon nitride rolling elements and races [2]. Since 1985 there have been considerable improvements in silicon nitride bearing materials and processes, which have led to substantial increases in bearing reliability. These have, in turn, led to commercial application of silicon nitride rolling element bearings and a growing experience base. This chapter reviews these developments.

II. POTENTIAL CERAMIC ROLLING ELEMENT BEARING MATERIALS

The properties that are desired of an advanced material for rolling element bearing application are listed in Table 1. Let us briefly review the importance of each property listed in the table and then examine the properties of various high performance ceramics to see which of them might have high potential as bearing materials.

Fracture toughness is often listed as a desired property for a bearing material. However, one must put this into the proper context. M-50 steel, the state-of-the-art high performance bearing steel, has a fracture toughness value of only about 15 MPa $\cdot$ $m^{1/2}$. As discussed later in this chapter, fully dense silicon nitride with an even lower fracture toughness of about 5 MPa $\cdot$ $m^{1/2}$ can provide significantly better bearing performance than M-50 steel. Thus, although if all other factors were equal one would chose a material with a higher fracture toughness, as one moves from one class of materials (steels) to another class of materials (silicon nitrides) it is evident that all factors are not equal. Nevertheless, within a given

Table 1 Desired Properties for Bearing Materials

Property	Range	Value
Fracture toughness, K_{IC}	High	>5 MN $m^{-3/2}$
Hardness	High	>1200 kg/mm^2
Elastic modulus	Low	<210 GPa
Density	Low	<4 Mg/m^3
Bend strength	High	>700 MPa
Corrosion resistance	High	
Upper use temperature	High	>800°C
Failure mode	"Steel-like" spallation	Small spalls

materials family (i.e., silicon nitrides), increasing fracture toughness probably would increase fatigue life and reduce wear, and therefore would be desired. Based on the foregoing reasoning, a fracture toughness value of at least 5MPa $\cdot$ $m^{1/2}$ is considered to be necessary for adequate bearing performance for ceramic materials.

Hardness is important for resistance to wear and abrasion. The elastic modulus determines the contact area and consequently the Hertzian stress at a given bearing load. The lower the elastic modulus, the lower the contact stress. If one is to use ceramic rolling elements with steel races (commonly referred to as a hybrid bearing), an elastic modulus lower than that of steel is desired. Since ceramics will have elastic modulii different from those of conventional bearing steels, modifications to bearing designs and to life prediction models are required.

Density (i.e., mass density) should be as low as possible to maintain low centrifugal loads, thus enabling the attainment of higher rotational speeds (or higher DN values, where DN is a rolling element bearing performance rating factor calculated by multiplying the bore diameter in millimeters by the shaft rpm). One must be careful that the low mass density is not obtained as a consequence of incorporating porosity into the microstructure. High strength and fatigue resistance require fully dense ceramics from a microstructural standpoint. It is well known that ceramic bearing life increases as porosity decreases [3]. The requirements for strength and corrosion resistance need no elaboration. The upper use temperature listed in Table 1 is far above that which any oil-lubricated bearing could tolerate. However, under lubrication starvation or dry lubricant conditions, such high temperature capability is to be desired.

Failure mode is not often listed as a material property. This is because the failure mode for a material is a function of the environment and the stress state. It may also stem from a natural tendency to design to avoid failure and therefore not to consider the consequences of failure. While designers and materials producers do their best to reduce the possibility of bearing element failure, they cannot entirely eliminate it. Therefore, when a bearing element does fail it must be in a relatively benign mode such as spalling, as opposed to catastrophic fracture. State-of-the-art M-50 steel fails by spallation. Any ceramic that is to be considered viable for rolling element bearing use must exhibit this failure mode. Additionally, if the candidate ceramic bearing material is to surpass M-50 steel's performance, spallation must occur at higher stresses and a higher number of fatigue cycles than in the case of this steel.

Table 2 lists the properties of several candidate bearing ceramics. How do these properties compare to the requirements just discussed? Only fully dense silicon nitride and transformation-toughened zirconia fail by spalling. Thus, other high performance ceramics such as alumina and silicon carbide are normally not used or advocated as rolling elements for bearings. Zirconia has a high fracture

Table 2 Properties of High Performance Structural Ceramics Versus M-50 Steel

Property	Silicon nitride: HIPed NBD-200	Silicon carbide: sintered	Alumina: fully dense sintered	Zironcia: sintered, transformation-toughened	M-50 steel: wrought ingot
Fracture toughness, K_{IC}, MN $m^{-3/2}$	5–6	4	5	8–10	12–16
Hardness, H, kg mm^{-2}	~1800–2000	~2800	~2000	~1300	~800
Elastic modulus, E, GPa	310	410	385	205	210
Density, Mg/m^3	3.2	3.1	4	5.6	8
Modulus of rupture, MPa	750	450	550	600–900	NA
Corrosion resistance	High	High	High	High	Moderate
Upper use temperature, °C[a]	1100	1400	1000^+	800–900	325
Failure mode	Spalling	Fracture	Fracture	Spalling	Spalling

[a]Based on temperature at which material loses so much hardness that wear behavior is likely to be affected.

toughness, high strength, and an elastic modulus very close to that of steel. Thus, one would expect that transformation-toughened zirconias would be utilized as ceramic rolling elements. However, early rolling contact fatigue tests of this material resulted in fatigue behavior considerably inferior to that of silicon nitride ceramics. For example, McLaughlin [4] performed comparative rolling contact fatigue (RCF) tests on several grades of silicon nitride, silicon carbide, and a transformation-toughened zirconia, all at a Hertzian stress of 5.9 GPa (860 ksi). The zirconia and the silicon carbides were both found to have average RCF lives two to three orders of magnitude less than any of the silicon nitrides. Thus, fully dense silicon nitride remains the preeminent ceramic for rolling element bearing application.

III. PERFORMANCE OF SILICON NITRIDE IN BEARING EVALUATION TESTS

A. Rolling Contact Fatigue

The increased rolling contact fatigue life of hot-pressed silicon nitride (HPSN) was demonstrated in the mid-1970s by Baumgartner [5] for rods and Dalal [6] for balls. Sibley [7] later documented the increased RCF life of HPSN balls compared to M-50 steel balls. The HPSN utilized in these early evaluations was NC-132, which contains about 1% MgO added as sintering aid. Improved versions of NC-132 have been developed utilizing hot isostatic pressing (HIP). The first of these, NBD-100, is essentially identical to NC-132 except that it is HIPed and consequently has less porosity and is isotropic. These improvements yield increased RCF performance, as shown in Figure 1 [8]. Figure 1 also illustrates one of the consequences of the higher modulus of silicon nitride as compared to steel, namely that at the same bearing load the ceramic will have a higher Hertzian stress (thus as shown in Fig. 1, silicon nitride is tested at a higher Hertz stress). A further improvement designated NBD-200 is processed similarly to NBD-100, except that extreme care is taken during powder processing to minimize tungsten carbide contamination due to milling. The benefits of this extra care are evident from the RCF performance of NBD-200 versus both M-50 steel and NBD-100, as shown in Figure 1.

The critical importance of surface finish to the RCF performance of HPSN was pointed out by Baumgartner [9], Dalal [6], and Sibley [7]. Dalal's data are reproduced in Table 3, which compares the fatigue lives of M-50 and NC-132 silicon nitride balls. The data show that the as-received silicon nitride balls have a significantly longer fatigue life than M-50 balls, but still fail by spallation. The data for the diamond-lapped (polished) silicon nitride balls indicate extremely long lives, and tests were terminated because the M-50 support balls failed, not the silicon nitride balls.

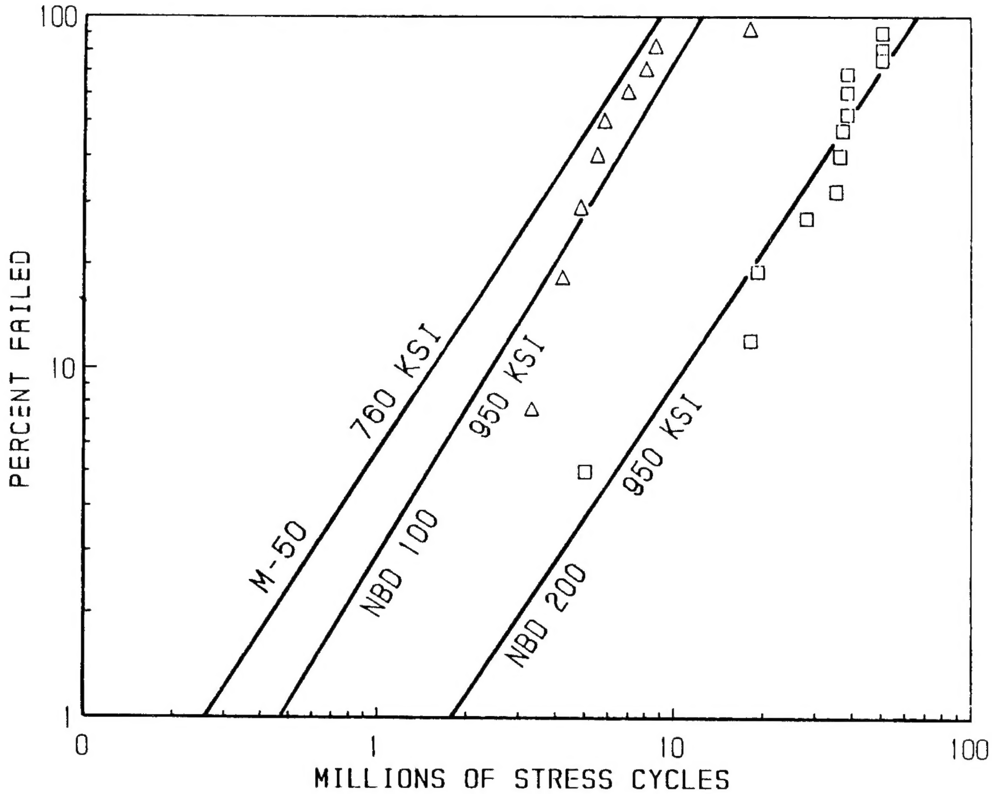

Figure 1 Rolling contact fatigue life of silicon nitride. (After Ref. 8.)

B. Lubrication Starvation Performance

Chui and Dalal [10] studied the effect of the elastohydrodynamic (EHD) lubrication on silicon nitride rolling element performance. Their work, as well as many subsequent tests, shows that HPSN gives EHD lubrication behavior essentially similar to that of steel with the same lubricants, inasmuch as:

1. It is wetted by hydrocarbon and ester lubricants "to a degree comparable to that for steel (based on contact angle measurements)."
2. In Hertzian contacts it forms "EHD lubricant films of thickness and traction properties very similar to those obtained with steel."

However, HPSN provides a unique capability, that is, lubrication starvation tolerance. Bersch [1] reports that a bearing with HPSN rollers survived a rig test for 117 hours with the lubricant shut off. The bearing condition at the end of this test was reported as "good"! Results of a lubrication starvation test of an all-NC-132 HPSN (except for the cage) roller bearing carried out in a small gas turbine engine have also been reported [2]. All components survived approximately one hour of full-speed testing in the engine.

The ability of HPSN to survive in very abusive environments was further

Table 3 Rolling Four-Ball Fatigue Life of Silicon Nitride Test Balls Stressed by M-50 Balls as a Function of Surface Finish

Spindle ball (test ball)	Spindle speed (rpm)	Maximum Hertzian stress [GPa (ksi)]	Number of M-50 support ball failures	Average test life ($\times 10^6$ rev)	Spindle ball condition post test
M-50: average of 6 tests	5,200	4.7 (680)	1 (in 6 tests)	13.2	6 of 6 spalled
As-received HPSN (NC-132)					
1 Test	5,200	4.7 (680)	2	117.3	Spalled
Average of 5 tests	10,000	5.5 (800)	4 (in 5 tests)	32.6	5 of 5 spalled
Diamond-lapped HPSN (NC-132): average of 6 tests	10,000	5.5 (800)	12 (in 6 tests)	170.9	5 of 6 intact (no spall)

Source: Reference 6.

substantiated by Hosang [11]. He reported two cases in which a hybrid bearing with HPSN balls and M-50 races, running at 93,000 rpm and a 200 N load, survived the complete destruction of the cage. Both the ceramic balls and the metallic races emerged in excellent condition.

Hanson and Ogden [12] have reported that ceramic rolling elements in metallic races significantly reduce lubricant breakdown. They attribute this advantage to the absence of microwelding between the ceramic elements and the races. This makes full ceramic or ceramic hybrid bearings attractive in situations characterized by the possible breakdown of an EHD film.

C. Failure Modes

Baumgartner [9] was the first to discuss the fatigue mechanism of HPSN, which he attributed to slow crack growth due to the nonelastic behavior of the material. The cracks ultimately link up and result in a spall. Lucek [13] has elaborated on the fatigue failure mechanism. In contrast to metals, where an accumulation of plastic deformation ultimately leads to cracking, in the fully dense silicon nitrides the mechanism is thought to be slow crack growth (akin to stress corrosion cracking). Alternatively, cyclic mechanical fatigue due to "far field" tensile stresses beyond the contact ellipse may be the cause of the progressive crack growth. Indeed, it has been shown by Beals and Bar-On [14] that for at least one variety of HPSN, cyclic mechanical fatigue cracks grow more rapidly than do static fatigue cracks (i.e., slow crack growth). Figure 2b shows a line of such cracks, which have coalesced to initiate the spall.

Whatever the precise details of the failure mechanism, the spalls exhibited in fully dense silicon nitride RCF test rods have remained remarkably constant in morphology over time. Figure 2a shows a spall from an RCF test of HPSN carried out by Baumgartner [5], and Figure 2b shows a spall in an RCF test of NBD-100 HIPed silicon nitride recently performed by Lucek [13]. The difference is that spalls in the improved material occur at either significantly higher Hertzian stresses or a higher number of stress cycles than earlier materials. In the absence of spallation, wear may eventually necessitate replacement of a bearing. Lucek [13] has evaluated the wear performance of several grades of fully dense silicon nitrides in RCF tests. Wear rates are a complex, not yet fully understood, function of the type and distribution of second phase, inclusion content, porosity, hardness, and fracture toughness. Table 4 shows the RCF and wear behavior of the silicon nitrides studied by Lucek. The L_{10} life listed in Table 4 is the fatigue life at which 10% of the rolling elements under test will fail.

It is important to reiterate that it is the existence of this noncatastrophic failure mode, identical to that of bearing steels, that differentiates silicon nitride from

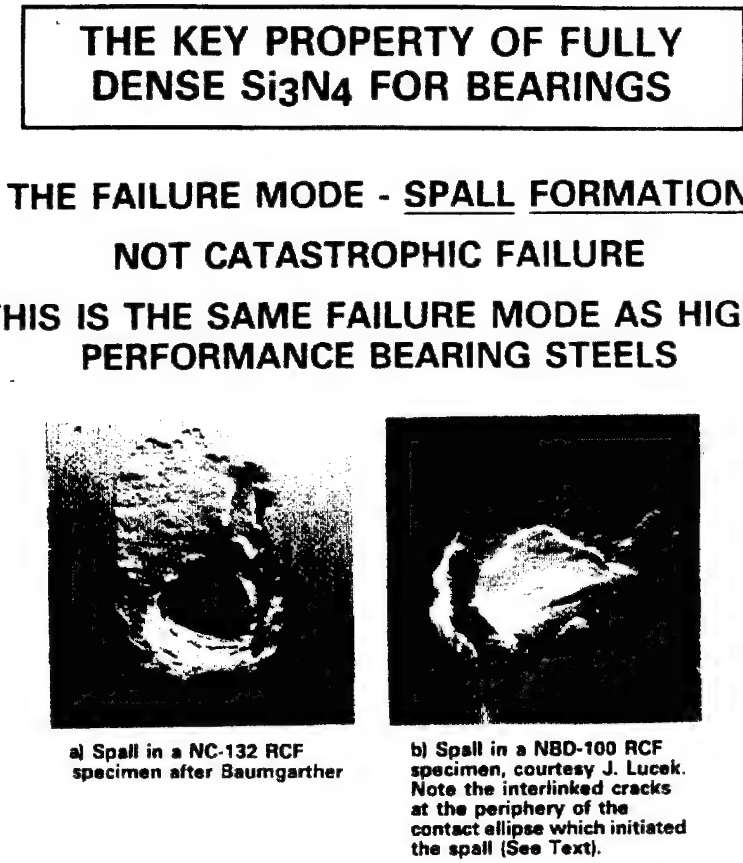

Figure 2 Spall morphology of silicon nitride resulting from RCF testing (spalls are approximately 0.75 mm at their longest dimension).

other ceramics and makes its use in high performance bearings acceptable to designers.

D. DN Performance

The low density of fully dense silicon nitride ($\approx$3.2 g/cm^3) compared to that of bearing steels ($\approx$8 g/cm^3) significantly reduces the centrifugal loads on the bearing races and rolling elements at any speed. Thus, one would anticipate that an all–silicon nitride or a silicon nitride hybrid bearing could attain a higher speed or DN rating than an all-steel bearing. Tests of both all–silicon nitride and hybrid bearings have confirmed this expectation. In general it has been found that hybrid rolling element bearings can attain DN ratings approximately 50% higher than all-M-50 bearings. Figure 3 shows the calculated increase in DN ratings for a specific 50 mm bore hybrid bearing as a function of bearing lifetime [15].

Table 4 Effect of Composition on Silicon Nitride Rolling Element Bearing Performance[a]

Material	Process	Hertzian stress (GPa)	L_{10} (10^6 cyc)	Weibull (m)	Wear ($m^3 \times 10^{-10}$)
7% Y_2O_3 + 5% Al_2O_3 (sialon)	Sintering	13.5	1.66	1.09	$\approx$1.6
5% Y_2O_3 + 2% Al_2O_3	Sintering and HIP	15.6	3.36	1.39	$\approx$0.25
1% MgO	Hot-pressing	16.4	0.58	0.59	$\approx$0.1
1% MgO	HIP (low WC)	16.5	>10.1	2.03	<0.1

[a]All RCF tests at 6.4 GPa; no information on grain size, morphology, starting powder, etc.; wear measured at 200 km element travel.
Source: Reference 13.

ratings for a specific 50 mm bore hybrid bearing as a function of bearing lifetime [15].

E. Heat Generation

Sibley [7] has pointed out that the heat generation in an all–silicon nitride or a hybrid silicon nitride–steel bearing will be lower than in an all steel bearing. Figure 4 shows the heat generation to be anticipated in two equivalent bearings: a conventional all-steel bearing and a hybrid with silicon nitride balls [15]. Two important points are made in this figure. First, at any given DN value the heat buildup of the ceramic element bearing is substantially less than the all-metal bearing. Second, confirming the performance described in the preceding paragraph, the DN limit is about 50% higher than that obtainable with the steel bearing. Recent studies by Aramoki et al. [16] relate the reduced temperature rise to the reduction of gyroscopic moments and centrifugal forces acting on the low mass density silicon nitride balls, which reduces frictional losses.

The paragraphs above have clearly shown the potential of fully dense silicon nitride rolling elements demonstrated in a variety of laboratory tests and in actual bearing tests. Given the high performance of these bearings, why have they seen

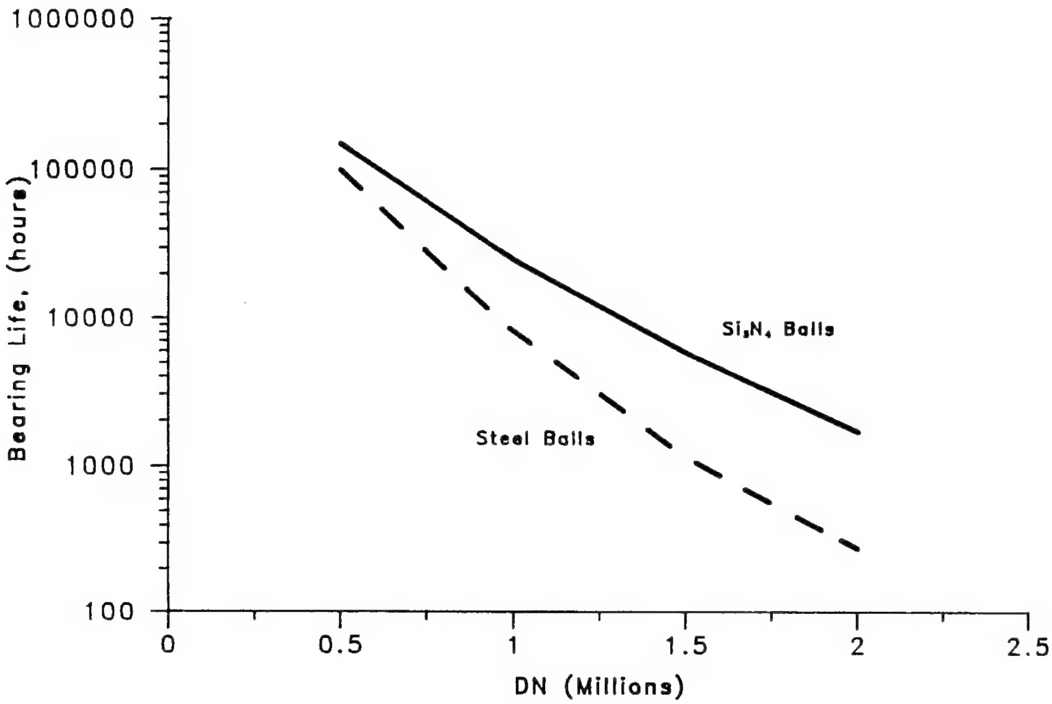

Figure 3 Calculated hybrid bearing life versus ball material. (From Ref. 15.)

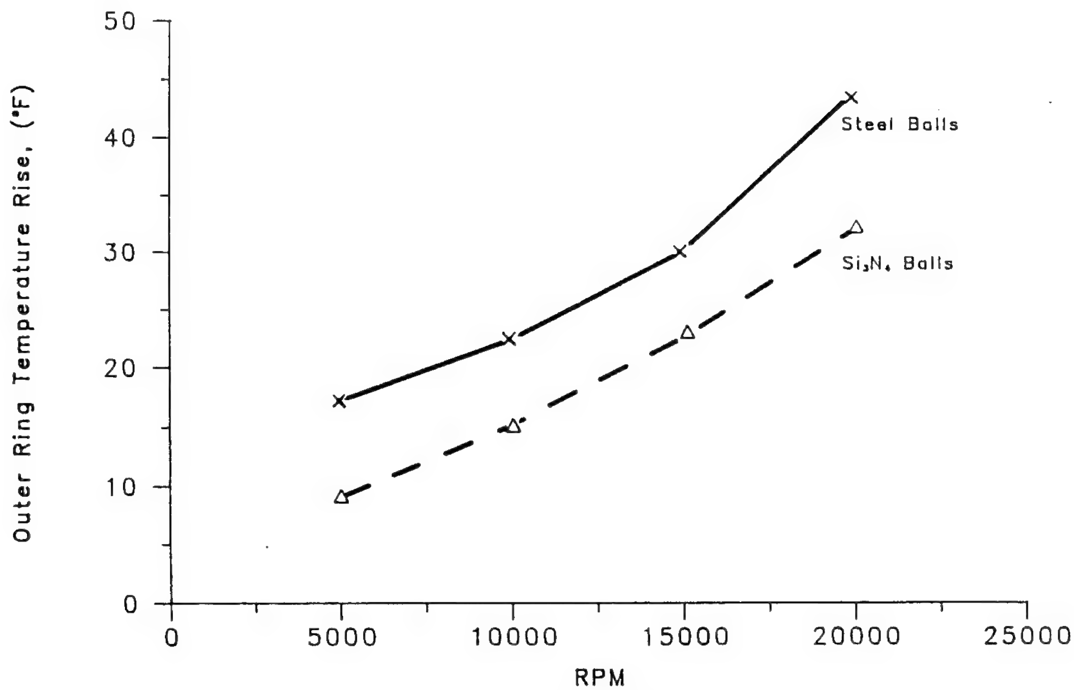

Figure 4 Bearing temperature rise versus speed. (From Ref. 15.)

such limited service to date? The two principal reasons are cost and the perception of inadequate reliability. Both these issues can be addressed and ameliorated by improved processing technology.

IV. PROCESSING AND RELIABILITY PROGRESS

Improved processing technology is the key to increasing the reliability and reducing the cost of silicon nitride rolling elements. Reliability ultimately translates into long life to failure, whether by spall formation or wear, and zero "infant mortality" or early failures. As discussed earlier by Katz and Hannoosh [2], reliability must be pursued by a total systems approach, which considers bearing design, processing, and quality assurance strategies as illustrated in Figure 5. Before the early to mid-1980s the standard silicon nitride rolling element material was hot-pressed with approximately 1% MgO densification aid (NC-132 type material). Because the material was hot-pressed, the strength, thermal conductivity, and several other properties were anisotropic. Processing runs were typically small in scale, and processing technology was rather immature. Although on the average early versions of NC-132 material out-performed M-50 steel, there were sufficient early failures to raise concerns about

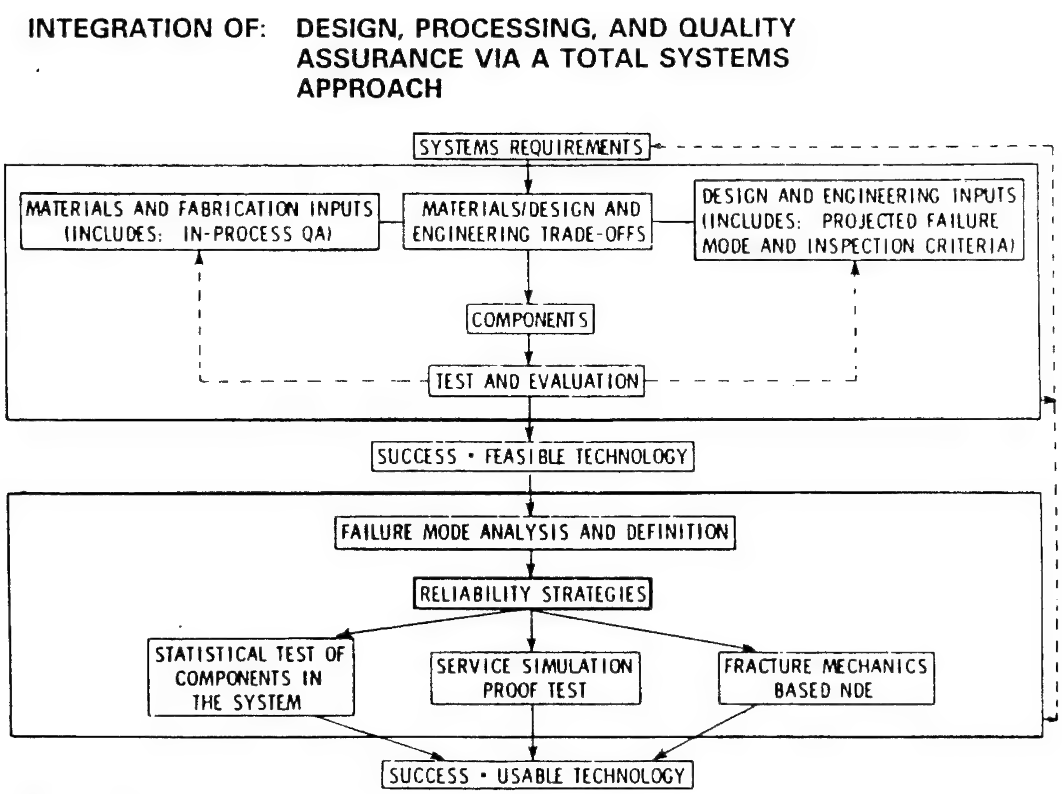

Figure 5 · A manufacturing strategy for assured reliability.

reliability. Process improvements, which stressed cleanliness and process control, significantly reduced or eliminated this problem with NC-132. Nevertheless there was a need to further increase the performance (life and wear) of silicon nitride bearing elements and to simultaneously address the perception of low reliability. Hot isostatic pressing coupled with even more stringent emphasis on cleanliness has lead to the improved performance illustrated in Figure 1, combined with increased reliability, as measured by increased L_{10} life and wear resistance shown in Table 4.

Another aspect of processing, which as already shown in Table 3 has a profound effect on bearing performance, is surface finishing. The best current practice—the use of diamond grinding and lapping (polishing)—produces excellent surface finishes but is expensive. Recently a new method for finishing silicon nitride bearings utilizing magnetic fluid grinding has been developed [17]. While the surface finish attainable by this method is not yet as good as obtained by diamond grinding and polishing, a finished ball can be produced in 1/40 the time. If this method can be further developed, it offers the prospect of significant cost reductions for silicon nitride rolling elements.

Processing development and optimization of fully dense silicon nitride for bearing applications could benefit greatly from studies relating composition, microstructural features (grain size and morphology, α/β phase ratios, percentage and distribution of grain boundary phases, percentage and distribution of porosity, etc.) and processing parameters to bearing element performance. Katz [18] has pointed out that very little of such information is available in the literature. Accordingly, studies aimed at providing information elucidating such relationships are a research priority.

V. APPLICATIONS OF CERAMIC ROLLING ELEMENT BEARINGS

The principal applications of ceramic rolling element bearings today are in the chemical, food, biotechnology, instrumentation, and machine tool markets. In overwhelming predominance, these bearings are made of fully dense silicon nitride. Steinmann [8] provides an example of a bearing for a chemical processing facility in which an all–silicon nitride bearing eliminated the need for a mechanical seal, saving an estimated $6000. More importantly, bearings that previously had a one-month service life have been replaced with bearings giving at least 4 years of service.

Hannoosh [19] cites an application of hybrid silicon nitride bearings to enable a machine tool spindle to operate at one million DN with grease lubrication. The cost tradeoffs of using more expensive ceramic bearings versus cost savings in the lubrication system are shown in Table 5. More importantly

than the initial systems savings ($700–$2200 per spindle) is the increased machining accuracy due to the higher stiffness and lower thermal expansion of the hybrid bearing.

Silicon nitride balls have just entered commercial service in turbomolecular pumps (Varian Turbo-V60). The bearings require no maintenance and contribute to the low vibration characteristics of this pump [20]. The potential of silicon nitride rolling elements to reduce noise levels in bearings for pumps and other machinery was recently reviewed by Philips [21].

An important exception to the general rule that high performance rolling element bearings are silicon nitride is the use of silicon carbide as rolling elements in pumps for offshore oil operations. The combination of resistance to abrasive wear and chemical resistance of SiC has made this material an attractive choice for relatively low DN (<500,000) centrifugal injection pumps lubricated only by seawater (which is highly abrasive due to entrained silica). Such pumps are reportedly in service in North Sea oil fields [22]. Hanson and Ogden [12] report the successful application of full ceramic bearings in tidal flow meters that operate immersed in seawater.

Future applications for full ceramic or hybrid ceramic bearings include bearings for use in strong magnetic fields or in marginaly lubricated applications. Hanson and Ogden [12] cite bearings for magnetic detectors for use in the superconducting supercollider as an example of the former and helicopter gearboxes as an example of the latter.

VI. SUMMARY

Advanced ceramic materials, principally silicon nitrides, possess combinations of material properties that make them the materials of choice for a variety of high performance rolling element bearing applications. During the past 10 years significant progress in processing technology has done much to reduce costs and

Table 5 Potential Cost Benefits of Ceramic Hybrid Bearings: A Case History

Application:
- Machine tool spindle bearing
- Silicon nitride bearing allows grease (vs. oil) lubrication at DN of 1×10^6 (vs. 0.6×10^6 for steel)
- DN of 1×10^6 was required

Cost:
- Silicon nitride hybrid bearing, added $800 per spindle
- Elimination of oil lubrication system saved $1500–$3000 per spindle
- Net savings: $700–$2200 per spindle

Source: Reference 19.

increase the reliability of ceramic rolling elements. Indeed these processing advances have been the basis for what is today a global market of approximately $10 million with growth potential to exceed $100 million by the end of the decade. It is important to note that this progress has been based on improved processing of silicon nitrides developed for hot components of gas turbine or other engines, not compositions developed specifically for bearing use. Future advances in this field will likely depend on the development of ceramic compositions and microstructures specifically designed for bearing application. The fundamental understanding of the composition/microstructure/processing/performance relationships that will enable such application-specific materials design is largely lacking.

REFERENCES

1. C. F. Bersch, Overview of ceramic bearing technology, in *Ceramics for High Performance Applications*, Vol. II, J. J. Burke, E. S. Lenoe, and R. N. Katz (Eds.), Brook Hill Publishing: Chestnut Hill, MA, 1978, pp. 397–405.
2. R. N. Katz and J. G. Hannoosh, Ceramics for high performance rolling element bearings: A review and assessment, *Int. J. High Technol. Ceram. 1*, 69–79 (1985).
3. E. V. Zaretsky, Ceramic bearings for use in gas turbine engines, *J. Tribol. ASME, 111*, 146–157 (1989).
4. J. J. McLaughlin, Alternate ceramic roller bearing program, Final Report, Contract No. N00019-81-C-0284 (November 1983).
5. H. R. Baumgartner, Evaluation of roller bearings containing hot-pressed silicon nitride rolling elements, in *Ceramics for High Performance Applications*, J. J. Burke, A. E. Gorum, and R. N. Katz (Eds.), Brook Hill Publishing: Chestnut Hill, MA, 1974, pp. 713–718.
6. H. Dalal, Machining bearings for turbine application, in *Ceramics for High Performance Applications*, Vol. II, J. J. Burke, E. S. Lenoe, and R. N. Katz (Eds.), Brook Hill Publishing: Chestnut Hill, MA, 1978, pp. 407–422.
7. L. B. Sibley, Silicon nitride bearing elements for high-speed high-temperature applications, in *Problems in Bearings and Lubrication*, AGARD Conference Proceedings No. 323, AGARD, Neuilly sur Seine, France, Chapter 5, 1982.
8. D. Steinmann, Silicon nitride ceramics for balls and ball bearings, *Ceram. Forum Int. 67*, 584–588 (1990).
9. H. R. Baumgartner, Ceramics bearings for turbine applications, in *Ceramics for High Performance Applications*, Vol. 2, J. J. Burke, E. S. Lenoe, and R. N. Katz (Eds.), Brook Hill Publishing: Chestnut Hill, MA, 1978, pp. 423–443.
10. Y. P. Chiu and H. Dalal, Lubricant interaction with silicon nitride in rolling contact interactions, in *Ceramics for High Performance Applications*, J. J. Burke, A. E. Gorum, and R. N. Katz (Eds.), Brook Hill Publishing: Chestnut Hill, MA, 1974, pp. 589–607.
11. G. W. Hosang, Results and design techniques from the application of ceramic ball bearings to the MERADCOM 10 kW turbine, presented at the AIAA/SAE/ASME/ASEE 23rd Joint Propulsion Conference, AIAA Paper No. 87-1444 (1987).

12. R. A. Hanson and W. P. Ogden, Ceramic bearings: The methods, the materials, the marketplace, *Split Ballbearing Features*, Vol. VII, Part 1, Split Ballbearing Division of MPB Corp. Lebanon, NH: 1991, pp. 1–7.
13. J. W. Lucek, Rolling wear of silicon nitride bearing materials, ASME Paper No. 90-GT-165 (1990).
14. J. T. Beals and I. Bar-On, Fracture toughness and fatigue crack propagation of silicon nitride with two different microstructures, *Ceram. Eng. Sci. Proc. 11*(7–8), 1061–1071 (1990).
15. Cerbec Ceramic Bearing Co., East Granby, CT, product literature, 1990.
16. H. Aramoki, Y. Shoda, Y. Morishita, and T. Sawamoto, The performance of ball bearings with silicon nitride balls in high speed spindles for machine tools, *J. Tribol. ASME, 110*, 693–697 (1988).
17. K. Kato, Tribology of ceramics, *Wear, 136*, 117–133 (1990).
18. R. N. Katz, presentation at the NIST/DARPA Ceramic Bearing Technology Workshop, Rockville, MD, April 17, 1991.
19. J. G. Hannoosh, *Design News*, Nov. 23, 1988.
20. Varian Vacuum Products, Lexington, MA, company product literature, 1991.
21. G. Phillips, presentation at the NIST/DARPA Ceramic Bearing Technology Workshop, Rockville, MD, April 17, 1991.
22. Anon., *Eng. Mater. Design*, March 1988, p. 11.

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